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The variable response of dryland corn yield to soil water content at planting

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ABSTRACT

Farmers in the central Great Plains want to diversify crop rotations from the traditional monoculture system of winter wheat-fallow. Corn (*Zea mays* L.) could work well as a rotation crop, but inputs are expensive and farmers would like to know the chances of producing a certain yield before investing in seed, fertilizer, herbicides, etc. Information on the yield response of corn to available soil water at planting could help guide the crop choice decision regarding corn. This study was conducted to determine if a predictive relationship exists between dryland corn yield and available soil water at planting time and, if such a relationship exists, to use it to assess the risk in obtaining profitable yields. Yield and soil water data from 10 years of a dryland crop rotation study at Akron, CO were analyzed by linear regression to determine predictive relationships. The yield-soil water content production function was highly variable, with values ranging from 0.0 to 67.3 kg ha^{-1} per mm of available soil water in the 0 to 1.8 m soil profile at planting. The differences in yield response to soil water were related to the amount and timing of precipitation that fell during the corn growing season. Because dryland corn yield is highly dependent on precipitation during reproductive and grain-filling stages, soil water content at corn planting cannot be used alone to reliably determine whether corn should be planted in a flexible rotational system. The predictive relationships developed in this study indicate that under typical amounts of available soil water at corn planting, profitable corn production under dryland conditions is a risky and speculative activity in the central Great Plains of the United States.

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1. Introduction

Profitable cropping systems in the semiarid central Great Plains must make efficient use of limited and highly variable precipitation. Additionally, cropping systems should be diversified, employing crop rotation systems that minimize disease, weed, and insect problems associated with monoculture. Several studies in this region have shown the potential for using corn in dryland crop rotations (Peterson et al., 1996; Anderson et al., 1999; Norwood, 2001; Halvorson et al., 2002). But corn production costs are high relative to other crops (Norwood and Currie, 1998), and yields can range widely due to the highly variable nature of precipitation (Norwood, 2001), both in timing and amount, and the high dependency of dryland corn grain yield to precipitation that falls just prior to silking through mid-grain-filling (Nielsen et al., 1996). Because of these factors, Great Plains dryland farmers would like a tool to help with the decision to plant corn. Such a tool could be developed if a strong and consistent relationship exists between available soil water at planting and corn grain yield. Probabilities of achieving given yield goals could be determined based on the amount of water available at planting and the probability of receiving a given amount of growing season precipitation.

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Previous research has shown relationships between available soil water content at planting and subsequent yields of some crops. Nielsen et al. (1999) reported that winter wheat (*Triticum aestivum* L.) yields were reduced by 7.9 kg ha^{-1} for each mm that soil water at wheat planting was reduced by the previous sunflower (*Helianthus annuus* L.) crop. Later Nielsen et al. (2002) showed that the response of winter wheat to available soil water at planting could be more accurately described by two linear relationships, one with a slope of 14.1 kg ha^{-1} mm^{-1} which was applicable to most growing season environmental conditions (87% of years), and one with a much less responsive slope of 5.0 kg ha^{-1} mm^{-1} that was seen when growing season conditions were very dry (April through June pan evaporation–precipitation > 65 cm). Norwood (2000) also reported reductions in winter wheat yields in Kansas related to lower soil water at planting. Lyon et al. (1995) showed that soil water at planting in western Nebraska was strongly correlated with dryland yield of short-season summer crops [pinto bean (*Phaseolus vulgaris* L.), proso millet (*Panicum miliacium* L.)], but only weakly related to yield of long-season summer crops [sunflower, grain sorghum (*Sorghum bicolor* (L.) Moench), corn]. They attributed this result in part to shorter season crops having more soil water available at the critical reproductive growth stage than longer season crops, which used much of the initial soil water for stover production and did not have it available for grain development. Norwood et al. (1990) showed dryland grain sorghum yield was strongly and positively correlated with available soil water at planting (28.4 kg ha^{-1} mm^{-1}) in western Kansas when averaged over 15 years, although the relationship was quite variable among years. Other factors that can influence dryland corn grain yield are plant population, fertility level, hail, and insect, disease, and weed pressures. But the primary factor controlling dryland corn grain yield in the semi-arid central Great Plains is available water from stored soil water and growing season precipitation (Campbell et al., 2005; Nielsen et al., 2005). The objective of this experiment was to quantify the dryland corn grain yield response to available soil water at planting to determine if a consistent predictive relationship exists that will aid farmers in making a crop choice at time of planting. If such a predictive relationship exists then a second objective was to use that relationship to determine the risk in producing profitable dryland corn.

Table 1 – Crop rotations that included corn and years that they were grown in the Alternative Crop Rotation Experiment, Akron, CO

Rotation	Years
C–DB	1995, 1996
C–M	1996
C–FM	1996
C–S	1992–1994
C–O–W	1995–1997
C–P–W	1998–2005
C–M–W	1992–2005
C–F–W	1992–2005
C–M–P–W	1997–2005
C–M–FP–W	1998–2005
C–M–W–W	1997–2005
C–M–F–W	1996–2005
C–S–F–W	1996–2005
OC	1995–2000

C = corn, DB = dry bean, M = proso millet, FM = foxtail millet (*Setaria italica* L. Beauv.), S = sunflower, O = oat (*Avena sativa* L., Poaceae), W = winter wheat, P = field pea (*Pisum sativum* L.), F = fallow, FP = forage pea (*Pisum sativum* L.), OC = opportunity cropping.

2. Materials and methods

This study was conducted at the USDA Central Great Plains Research Station, 6.4 km east of Akron, CO (40°09′N, 103°09′W, 1384 m). The soil type was a Weld silt loam (fine, smectitic, mesic Aridic Argiustoll) approximately 200 cm deep. In 1990, several rotations were established to investigate the possibility of cropping more frequently than every other year, as done with the traditional winter wheat-fallow system. A description of the plot area, tillage systems, and experimental design are given in Bowman and Halvorson (1997) and Anderson et al. (1999). Briefly, rotation treatments were established in a

Table 2 – Planting, harvesting, and fertilizing details for corn in the Alternative Crop Rotation Experiment, Akron, CO, 1992–2001

Year	Variety	Planting date	Harvest date	Seeding rate (seeds ha^{-1})	Fertilizer	
					(kg N ha^{-1})	(kg P_2O_5 ha^{-1})
1992	Pioneer 3732	4 May 1992	2 November 1992	36,800	94	–
1993	Pioneer 3732	10 May 1993	27 October 1993	36,800	90	–
1994	Pioneer 3732	6 May 1994	14 October 1994	39,770	90	–
1995	Pioneer 3732	18 May 1995	21 October 1995	36,800	66	–
1996	Pioneer 3732	1 May 1996	7 October 1996	36,800	78	–
1997	Pioneer 3732	1 May 1997	7 October 1997	36,800	45	17
1998	DK 493BT	12 May 1998	5 October 1998	39,780	67	17
1999	DK 493BT	7 May 1999	12 October 1999	39,780	34	17
2000	DKC49-92	10 May 2000	12 September 2000	39,780	84	17
2001	NK4242BT	16 May 2001	23 October 2001	41,020	90	22
2002	NK4242BT	5 May 2002	No harvest	41,000	67	22
2003	NK4242BT	21 May 2003	7 October 2003	34,580	67	22
2004	N42B7	3 June 2004	26 October 2004	29,640	67	22
2005	N42B7	18 May 2005	3 November 2005	29,640	77	–

randomized complete block design with three replications. All phases of each rotation were present every year. Individual plot size was 9.1 m × 30.5 m, with east–west row direction. The current study analyzes data from the 1992 through 2005 crop growing seasons from all crop rotations utilizing corn (Table 1). The corn hybrids were 101-day relative maturity hybrids from 1992 to 1997 and 99-day relative maturity hybrids from 1998 to 2005. The rotations used contact and residual herbicides for all weed control. Specific details regarding hybrids, planting and harvest dates, and seeding and fertilization rates are given in Table 2.

Available soil water in the 0–180 cm soil profile was measured at planting using time-domain reflectometry in the 0–0.3 m layer and a neutron probe at 0.45, 0.75, 1.05, 1.35, and 1.65 m depths. The neutron probe was calibrated against gravimetric soil water samples taken in the plot area. Gravimetric soil water was converted to volumetric water by multiplying by the soil bulk density for each depth. Two measurement sites were located near the center of each plot and data from the two sites were averaged to give one reading of soil water content at each sampling depth per plot.

Available water per sampling depth was calculated as:

(Volumetric water − lower limit) × (layer thickness)

where volumetric water = m^3 water m^{-3} soil from neutron probe or time-domain reflectometry, lower limit = lowest volumetric water observed (Ritchie, 1981; Ratliff et al., 1983), layer thickness = 0.3 m.

The specific values of lower limits for corn that were used were 0.110, 0.135, 0.087, 0.074, 0.079, and 0.101 $m^3\ m^{-3}$ for the 0–0.3, 0.3–0.6, 0.6–0.9, 0.9–1.2, 1.2–1.5, and 1.5–1.8 m soil depths, respectively (Nielsen et al., 2006). The relationships between available soil water at planting and corn grain yield (reported at 0.155 kg kg^{-1}) were analyzed by linear regression using Statistix 9 software (Analytical Software, 2008).

3. Results and discussion

Available soil water at corn planting ranged widely from 27 to 350 mm in the 180 cm soil profile as influenced by precipitation, previous crop, and intensity of crop rotation over the 14 year of the study (Fig. 1a). Similarly, corn grain yield ranged widely from 0 to 5280 kg ha^{-1}. From the data presented in Fig. 1a, there appears to be no consistent relationship between available soil water at planting and corn yield. For example, an extremely dry soil profile at planting (69 mm available soil water) gave a yield of 5280 kg ha^{-1} in one year (1999) and a yield of only 1590 kg ha^{-1} in another year (1993). On the other hand, an essentially full profile of 320 mm available soil water at planting was associated with a yield of only 2045 kg ha^{-1} in 1995 but also more than twice as much (4530 kg ha^{-1}) in 2001. However, when the data are presented by year (arbitrarily separated into Fig. 1b and c to improve clarity), some linear relationships appear to exist.

Seven distinct responses exist in the data, with slopes ranging from 67.3 kg ha^{-1} (1999) to 0.0 kg ha^{-1} (2002) (Table 3). No grain yield formed in 2002 (Fig. 1c), regardless of available soil water at planting, when only 15 mm of precipitation was recorded during the critical 15 July to 25 August period (just

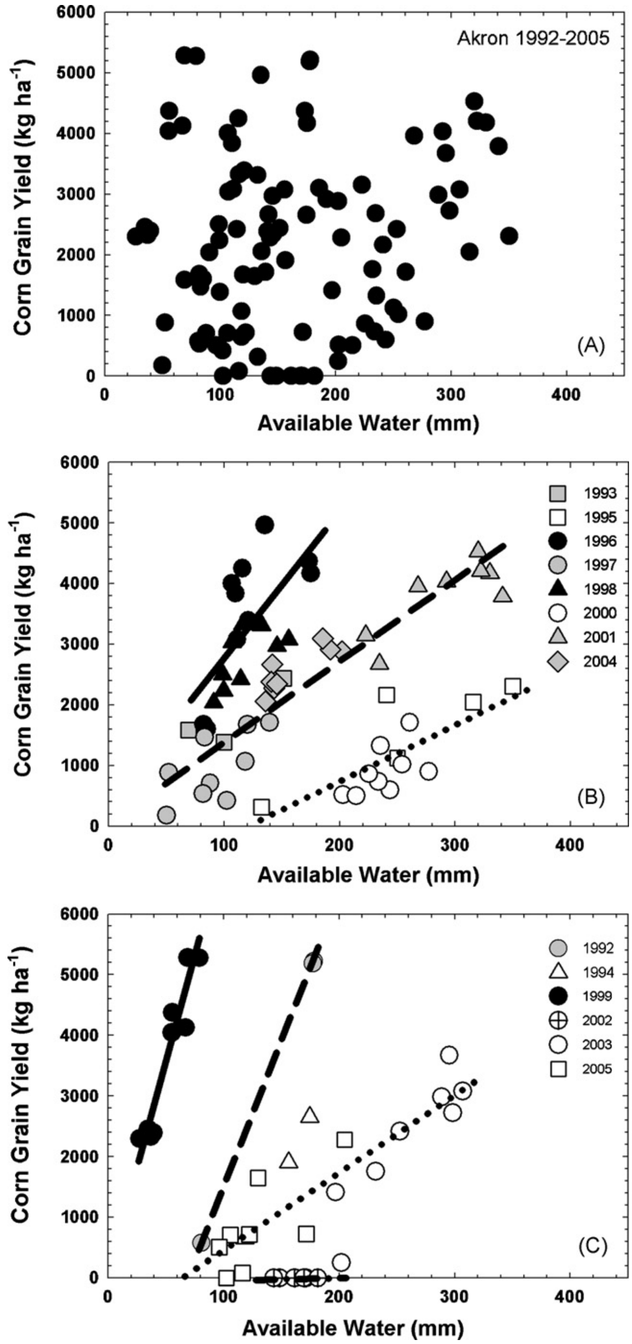

Fig. 1 – Response of dryland corn grain yield to available soil water (0–180 cm profile) at planting, Akron, CO.

prior to tasseling through dough [R4]). At the other extreme was the yield response of 67.3 kg ha^{-1} for each additional mm of available soil water at planting recorded in 1999 when 167 mm of precipitation fell during the critical period (Fig. 1c). The other five responses were intermediate to these two extremes (Table 3), and were generally related to amount of precipitation falling during the 6-week critical period surrounding tasseling and mid-grain-filling (Table 3).

The slopes of the three low responses (9.9 kg ha^{-1} mm^{-1} [1995/2000]; 12.9 kg ha^{-1} mm^{-1} [1994/2003/2005]; 13.1 kg ha^{-1} mm^{-1} [1993/1997/2001/2004]) were not different from one

Table 3 – X-axis offsets (a), slopes (b), and coefficients of determination (R^2) for linear regressions (model kg ha^{-1} = b × [mm − a]) of corn grain yield on available soil water at planting shown in Fig. 2b and c; and critical period precipitation classes for precipitation falling between 15 July and 25 August at Akron, CO

Years	N	X-axis offset (a) (kg ha^{-1})	Slope (b) (kg ha^{-1} mm^{-1})	R^2	Critical period precipitation[a]
1999	9	−2	67.3	0.91	High
1992	3	69	47.8	1.00	High
1996, 1998	19	−19	22.9	0.43	Medium, medium
1993, 1997, 2001, 2004	28	−7	13.1	0.87	Medium, medium, medium, medium
1994, 2003, 2005	19	65	12.9	0.69	Low, low medium
1995, 2000	14	129	9.9	0.57	Low, low
2002	8	163	0.0	1.00	Low

N = number of observations.
[a] High = more than 125 mm precipitation falling between 15 July and 25 August; low = less than 70 mm precipitation falling between 15 July and 25 August.

another (P = 0.50), but the X-axis offsets were different from each other ($P < 0.01$). No obvious differences in precipitation amounts during vegetative development or late grain-filling (Table 4) appear to explain either the general differences in regression offset position or the higher yields for a given available soil water at planting for the 1993/1997/2001/2004 data than for the 1994/2003/2005 or 1995/2000 data. The slopes of the two high response data sets (47.8 kg ha^{-1} mm^{-1} [1992]; 67.3 kg ha^{-1} mm^{-1} [1999]) were not different from each other (P = 0.06), but the offsets were different from each other ($P < 0.01$). The slope of the 1996/1998 data (22.9 kg ha^{-1} mm^{-1}) −1) was different from the 1999 data ($P < 0.01$) with different offsets ($P < 0.01$). Likewise, the slope and the offset of the 1996/1998 data were different from the 1992 data ($P < 0.01$).

The variable corn grain yield response to available soil water at planting (regression slope) is seen clearly in Fig. 2. As amount of precipitation falling during the critical pre-tassel to mid-grain-filling period increased, so did the response of grain yield to available water. We fit two linear regressions to the data (Fig. 2):

$$\text{Slope} = -0.6492 + 0.16889\,\text{mm}, \quad R^2 = 0.85, \quad n = 4 \tag{1}$$

$$\text{Slope} = -52.9797 + 0.73337\,\text{mm}, \quad R^2 = 0.98, \quad n = 4 \tag{2}$$

The regressions intersect at a critical period precipitation value of 93 mm.

Lyon et al. (2003) simulated corn grain yields for another central Great Plains location (Sidney, NE) about 125 km north of the current study. Using the Agricultural Production Systems Simulator (APSIM; Keating et al., 2003) to simulate yield from 1948 to 2001, they found grain yield response to soil water at planting ranging from 8.25 kg ha^{-1} mm^{-1} for a plant density of 3 plants m^{-2} to 12.57 kg ha^{-1} mm^{-1} for a plant density of 4 plants m^{-2}. The average seeding rate in the current study was 3.75 seeds m^{-2}. The average post-flowering precipitation reported for Sidney was 67 mm. Using 67 mm in Eq. (1) predicts a yield response to soil water of 10.67 kg ha^{-1} mm^{-1}, which is approximately the average of the two responses constructed from the Sidney simulations. These simulation results provide some additional evidence to validate the accuracy of Eq. (1).

Table 4 – Precipitation at Akron, CO (1992–2005 and 42-year average)

Year	Planting-14 July (mm)	15 July–25 August (mm)	26 August–30 September (mm)	Total
1992	154	132	5	291
1993	96	112	24	232
1994	66	58	12	136
1995	199	30	64	293
1996	234	77	106	417
1997	138	72	43	253
1998	54	124	8	186
1999	121	167	80	368
2000	54	70	71	195
2001	108	96	45	249
2002	55	15	111	181
2003	138	35	22	195
2004	82	99	50	231
2005	190	110	10	310
Average (1964–2005)	136	88	32	256

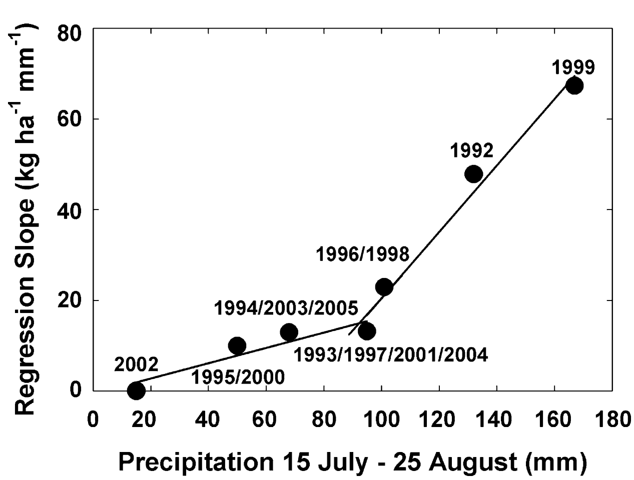

Fig. 2 – Relationship between critical period (15 July to 25 August) precipitation and the slope of the regression of dryland corn grain yield on available soil water (0–180 cm profile) at planting, Akron, CO.

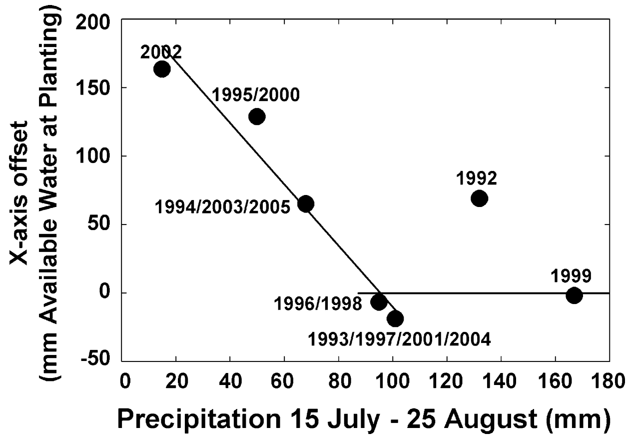

Fig. 3 – Relationship between critical period (15 July to 25 August) precipitation and the X-axis offset for the regression of dryland corn grain yield on available soil water (0–180 cm profile) at planting, Akron, CO.

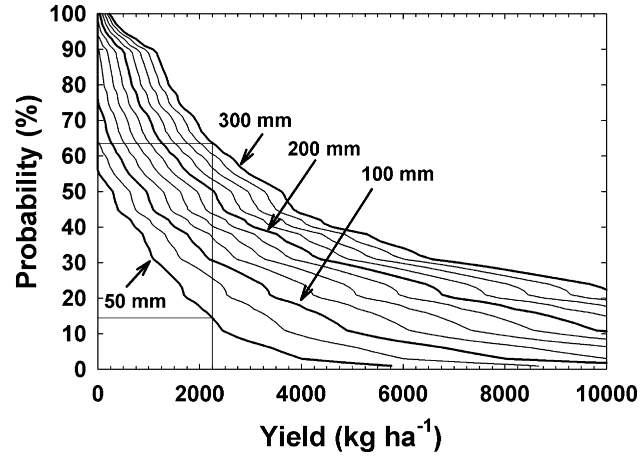

Fig. 4 – Probability of obtaining a corn yield based on 1908–2007 precipitation (15 July to 25 August) at Akron, CO with various amounts of available stored soil water (0–180 cm profile) at planting (50–300 mm in 25 mm increments).

We also investigated a relationship between the regression X-axis offsets shown in Table 3 and critical period precipitation. Those data also appear to fall into two groups, as shown in Fig. 3. The regression offsets decline linearly with increasing amount of critical period precipitation according to the following relationship

$$\text{Offset} = 214 - 2.2449\,\text{mm}, \quad R^2 = 0.96, \quad n = 5 \tag{3}$$

A logical explanation would be that the influence of available soil water at planting on corn yield declines in importance as critical period precipitation increases. Stated differently, when critical period precipitation is low, corn yield is more dependent on available soil water at planting than when precipitation in July and August is high. We propose that when critical period precipitation is greater than about 95 mm the regression offset is zero. This can be visualized better by looking at the regression lines in Fig. 1 and Table 3 and noting that for three data sets (1999, 1996/1998, and 1993/1997/2001/2004) the regressions go approximately through the origin. We have chosen to exclude the offset for 1992 in this analysis because it appears to be an outlier in Fig. 3. Fig. 1c shows that only three data points are used to create the regression for 1992. A small error in the low yield point could make a very large difference in the calculated slope and offset. We are much more confident in the regression offset values calculated to be very near zero for the 1999 data set ($N = 9$), 1996/1998 data set ($N = 19$), and the 1993/1997/2001/2004 data set ($N = 28$).

Using Eqs. (1)–(3), and assuming that the regression offset is zero when critical period precipitation is greater than 94 mm, we calculated probability distributions of dryland corn yield for situations in which available soil water at planting ranged from 50 to 300 mm (Fig. 4). We used the long-term precipitation record at Akron (1908–2007) to determine the distribution of precipitation in the 15 July to 25 August period. Those precipitation values were used with equations 1, 2, and 3 to determine appropriate yield responses to available soil water at planting. For example, based on the long-term precipitation record, Fig. 4 indicates a corn yield of 2250 kg ha^{-1} (considered by farmers in the region to be a break-even yield) would occur 14% of the time if 50 mm of soil water were available at planting, while that same yield could be expected 63% of the time if 300 mm were available at planting (about field capacity for the 180 cm soil profile of a silt loam). The reader is cautioned to keep in mind that 2250 kg ha^{-1} is probably a conservative estimate of a break-even yield, as corn prices have increased dramatically since 2006.

Lyon et al. (2003) concluded from their simulation studies at Sidney, NE that dryland corn should not be planted when available soil water at planting was less than 80 mm. That conclusion should probably be qualified as Fig. 1 shows that over several years at Akron 80 mm or less of available soil water at planting resulted in yields ranging from 175 to 5280 kg ha^{-1}. Fig. 4 allows a farmer to more accurately assess the risk associated with planting corn with only 80 mm of soil water available at planting by showing that the probability of obtaining a break-even yield of 2250 kg ha^{-1} would be 27%. While that is a fairly low percentage on which to base a fairly large investment for the inputs required to grow corn, Fig. 4 still shows that approximately one-fourth of the years would provide sufficient precipitation during the critical 6 week period of development to produce a break-even yield or better.

Our results indicate quite a different conclusion than that of Lyon et al. (2003) for years with a full soil water profile at planting. Their results indicated essentially no chance of an unprofitable corn yield with 240 mm of available soil water at planting. Fig. 4 shows only a 55% chance of producing a break-even yield with that amount of soil water due to the highly variable nature of precipitation from 15 July to 25 August.

During the course of the alternative crop rotation experiment (1992–2007) available soil water at corn planting has averaged 204 mm for the corn-fallow-wheat rotation. The distribution of available soil water at corn planting shown in Fig. 5 indicates that the probability of having 204 mm of soil water at planting is 44%. With 204 mm of available soil water at planting a yield of 2250 kg ha^{-1} would be expected to occur

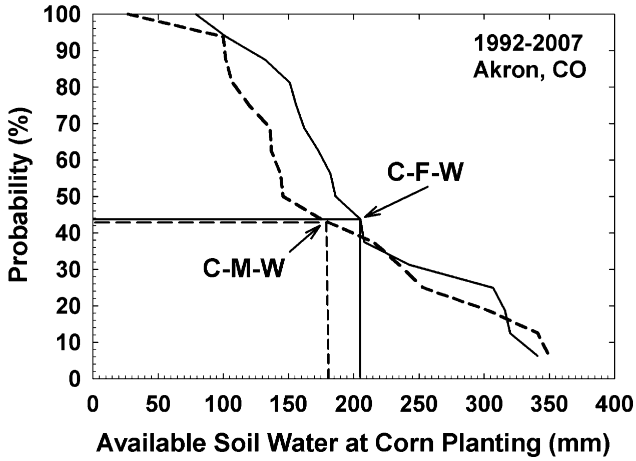

Fig. 5 – Probability at least a given amount of available soil water (0–180 cm profile) at corn planting at Akron, CO in a corn-fallow-wheat (C-F-W) rotation or a corn-proso millet-wheat (C-M-W) rotation.

51% of the time. Therefore the probability of achieving this break-even yield with average starting soil water would be 22%. With that same amount of soil water at planting a yield if 5000 kg ha^{-1} would occur about 29% of the time, making the probability of achieving that yield with average starting soil water 15%. With a more intensive rotation of corn-proso millet-wheat, available soil water content at planting averaged 181 mm, occurring 44% of the time. With that amount of soil water at planting a yield of 2250 kg ha^{-1} would be expected to occur only 35% of the time and the probability of achieving the break-even yield with average starting soil water would be 15%. A yield of 5000 kg ha^{-1} would occur only about 16% of the time, making the probability of achieving that higher yield with average starting soil water only 7%.

4. Conclusions

The two relationships reported by Nielsen et al. (2002) for winter wheat grain yield response to available soil water at planting could be useful for tactical crop selection purposes because one relationship was applicable to most of the growing season conditions that would follow, while the second relationship was applicable to only the 13% driest, most water-demanding growing season conditions. In contrast, the data reported in the current study indicate that the response of corn grain yield to available soil water at planting is much more variable such that knowledge of amount of available water at planting without a reliable forecast of growing season precipitation is not sufficient information to adequately predict corn grain yield. The response of dryland corn yield to soil water at planting varies with amount of precipitation in the critical yield formation period (15 July to 25 August). The predictable nature of those responses to amount of critical period precipitation allow for an estimation of corn yield probability from the long-term precipitation record when an amount of available soil water at planting is specified. Similar probability estimates could be generated for other central Great Plains locations where long-term precipitation records exist. The yield probabilities generated from the Akron, CO critical period precipitation record confirm the highly risky nature of dryland corn production in the central Great Plains. On the other hand, the data from this study showed clearly that there is always a positive response of corn grain yield to increasing available soil water at planting under dryland conditions, confirming the recommendation that every effort should be employed to increase precipitation storage efficiency during non-crop periods through good residue management and weed control.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agwat.2008.08.011.

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